# Hydrological Processes and Potential Water Resources in the Mekong River Basin(メコン河流域における水文過程と可能水資源量)

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# 論文内容要旨

## Hydrological Processes and Potential Water Resources in the Mekong River Basin

Availability of Geographical Information System (GIS) data sets of watershed physical properties such as land use, soil types, geology and the advancements gained in obtaining distributed meteorological variables with the help of GIS have stimulated the development of physically based hydrological models. Controlled water storage and release activities in reservoirs and irrigated crop fields affect the hydrological cycle of large-scale watersheds. Water storing devices have been constructed to meet water demands especially for agriculture and power supply with increasing population. However, some of those human activities have adversely resulted in insufficient water resources and harmful environmental impacts in downstream locations. Sound hydrological models are necessary to simulate hydrological processes in order to avoid harmful impacts to ecological stability and to achieve the state of sustainability.

The Mekong River is the twelfth longest river, 8th largest river in terms of annual runoff and on of the world's least exploited major water course in terms of dams and water diversions. It begins its 4,200 km journey through steep mountainous gorges in China. It gathers runoff contributions from an area of 795,500 km$^2$ before meeting the South China Sea. Fed by melting snow on the Tibetan Himalayas and monsoon rains, the river nourishes lives of over 60 millions of peoples who live in countries which it flows through. It covers all of Lao PDR and Cambodia, a large part of Thailand, the delta and central highland in Vietnam, the eastern part of Myanmar and a small area of China. Annual discharge from the watershed into the South China Sea is about 475,000 MCM. Eighteen percent of total runoff comes from the upper basin of 24 % of the total basin area. Approximately 55% of the total discharge comes from the left bank tributaries in Laos and Cambodia, which represent about 28 % of the total drainage area. Northern Thailand with 19 % of the basin area contributes only 10% of the discharge. In April the flow is ordinarily at its lowest. In May or June as the monsoon rain moves in from the south, the flow begins to increase, doing so most rapidly in the eastern and northern highlands. The highest water levels are reached as early as August or September in the upper reaches and as late as October in the southern reaches. The climate of the Mekong basin is dominated by two distinct monsoons. The rainy southwest monsoon, which occurs from Mid May to early October, is the main source of precipitation to the region. The normal annual rainfall in the region varies from 1000 mm near Khon Kaen in North-eastern Thailand to 4000 mm in the mountainous fringes of the basins lying in Laos, Cambodia and Vietnam. About 88 % of the annual rainfall falls between May and October. Melting snow in Tibet and Yunnan from March to June and dry northeast monsoon from October to March only account for about 10 % of the total precipitation. Temperatures in the lower Mekong basin are uniformly warm throughout the year. Daily highs at Phnom Penh average is about 32º C, where as lows average about 23º C. Small differences can be traced with elevation differences and to seasonal variations. The mean relative humidity of the atmosphere is highest in September slightly higher than 80 % and lowest in March just over 60 %. The Mekong river basins land cover mainly composed of irrigated land and forest. The forests in the basin have undergone periodic cleaning and re-growth due to many generations of widespread agriculture. The basin forests comprise of two major groups namely: evergreen and deciduous.

Drainage structure of a watershed is the water course carrying water flow under gravity. It is also the path for the sediment and contaminated materials. Hydrological modelers, those who go beyond the lumped concept, need to determine accurate internal drainage structure to route locally generated flow, sediment and pollutants to their final destination. Availability of global grid Digital Elevation Models (DEMs) has stimulated the development of automatic procedures that alleviate the burden of some typical hydrological pre-requirements (e.g. drainage basin and subbasin delineation, drainage path calculation, drainage network extraction).

Conventional approach to determine the internal drainage structure uses eight-flow direction matrix (D8) derived from raster DEM. The individual cells are connected to each other by their respective drainage directions and are thus organized into drainage basins. Each cell either drains into one of the eight neighboring cells or into none if the cell represents an inland sink or a basin outlet to the ocean. In distributed hydrological modeling, continuous drainage network where each grid cell must be directly connected to one of its neighboring cells, the eight flow directions (D8) is a valid approach to model the watershed drainage structure. Numerous algorithms based on the D8 approach have been reported to treat depression points and flat areas. In the study, an algorithm as a function of the minimum elevation of the surrounded eight grids and location is applied to remove both depression points and flat areas in the DEM which used to exact the drainage structure of the Mekong river basin. The best value for the parameter C is 0.1 for the 3 arc minute resolution DEM. The main demerit of this approach is lack of information on depression points and flat areas. Although different approaches have been applied to extract stream network by modifying original DEM, applicability of these methods are in question when applying to a large-scale watershed. It is difficult to obtain a good agreement between modeled river networks with the actual one especially for the large watersheds. This is a major draw back in distributed hydrological modeling where flow is transported via a modeled watersheds drainage structure. In the study usage of available river and lake network was suggested for a better watershed delineation.

New approaches are used to determine drainage structure in large watersheds using available land use and elevation data sets. A Digital River and Lake Network (DRLN) is created using land use data. DRLN is used as an ancillary data source to remove depression points in the DEM to generate watersheds' drainage structure. Elevation of the depression points and flat area cells which lies outside of the DRLN were changed using an algorithm similar to the one used in conventional approach. Instead of the location, distance to the nearest DRLN cell was used in the equation. According to the algorithm, perturbation coefficient takes a larger value for cells closer to the DRLN and it tends toward zero for cells far from the DRLN. The algorithm was tested for the 1 km resolution data set of Mekong river basin till Pakse gauging station. And the results as well as advantages are discussed.

Since the flow direction of lake cell cannot be determined with a downstream cell, distance between a lake outlet and the lake cell was minimized to assign flow direction of a lake cell. Elevations of all DRLN cells are lower from arbitrary value (10 m). Depressions and flat points in the river segments were removed with the help of the conventional algorithm. Starting from the outlet, the algorithm goes along upstream following the outline of the digital river network (DRN) and assigns the flow directions of visited cells so that each cell flows into the cell located directly down-stream. Development of a watershed's drainage structure using ancillary data of DRLN not only minimize the disturbance to DEM while removing depression points and flat areas in DEM, but also produces a accurate drainage network. DRLN of the watershed can be used to circumvent the fundamental errors of D8 approach due to lack of information on sinks in the DEM.

TOPMODEL is a parsimonious physically-conceived-semi-distributed catchment scale rainfall runoff model based on spatially distributed soil topographic index. Introduction of block wise approach to the TOPMODEL with Muskingum-Cunge flow routing method (BTOPMC) has enhanced the applicability of TOPMODEL from hundreds of square kilometers to several ten thousands square kilometers river basins. In the block wise approach, a watershed is divided into blocks and local saturation deficit which controls the depth to the saturation zone is calculated with respect to the block average saturation deficit value. Four model parameters namely, lateral transmissivity under saturated conditions, decay factor, maximum root zone storage, and flood plain Manning's coefficient, are assigned as functions of land use, extracted from USGS (United States Geological Survey) global land cover characteristics database.

Saturation deficit depends both on depth to the saturation zone from the surface zone and the soil properties in the unsaturated zone. Optimum block size may depend on topographic properties as well. TOPMODEL is a topographically based model and simulation results strongly depend on topographical features (elevation and slope) of the study area. For a flat watershed, a large block size may be suitable because of the less standard deviation in saturation deficit. On the other hand, small block size may be need to accurately model watersheds with complex water table profile. If standard deviation of soil topographic index is very high over a block, it may results in abrupt changes in saturation deficit requesting a change in the block size. Simulations were carried out to understand the underneath behavior of assigning different number of blocks. It was found that the optimum number of blocks, which results in maximum simulation efficiencies produces the maximum standard deviation of block average soil topographic index.

The BTOPMC model is used to simulate hydrological processes in the effective watershed of 277,000 square kilometers from Luang Prabang to Pakse in Lao PDR along the Mekong River. Reservoir activities in the watershed are taken into account using simplified ruling curves determined by the purposes of the operation and catchment area. Water storages and releases from irrigated crop fields are taken into account by introducing desirable water level function to the relevant grids. The Manning's coefficient along the main stream and tributaries are assigned as a function of slope and the best Manning's coefficient value at the most downstream location. Average Manning's coefficient values found for both the main river and tributaries are 0.029 and 0.034, respectively. Annual evapotranspiration is estimated based on a pixel wise methodology related to potential evapotranspiration. Potential water resources distributions at 1 and 100 square kilometer grid size are estimated and presented. It has been found that there is sufficient water resources in mountainous areas in Lao PDR whereas flat irrigated fields in Thailand need to get water from nearest potential locations to meet their requirement.

Nash-Sutcliffe coefficient was used to evaluate the simulation accuracy. The efficiency coefficients were estimated for five gauging stations along the main stream. The value ranges from 93.5% to 95.4%. Simulation accuracy has significantly improved after considering intentional water storages and releases activities in the watershed. Hydrological simulations were performed for the Mekong river basin till Pakse and incapability of modeling human activities such as reservoir operations and temporary water storages in irrigated crop fields were clearly visible from the results. Simulations results were used to discuss the temporary water storage functions in the region. Hydrological processes were thoroughly studied for the effective watershed from Luang Prabang to Pakse with 1 kilometer resolution. Hydrological processes are discussed at different climatic regions of the basin. Sub-basins annual evapotranspiration ranges from 470 mm to 620 mm. Average actual ET of different land use types were estimated and it varies from 563 mm in semi desert to 875 in irrigated crop fields. It was found that in lesser rainfall areas, 95% of the days in a year produce daily runoff that is less than that of basin average. The figures are 88% and 57% for an average and higher rainfall areas respectively. It has been found that there is sufficient water resources in mountainous areas in Lao PDR whereas flat irrigated fields in Thailand need to get water from nearest potential locations to meet their requirement.

# 論文審査結果の要旨

メコン河流域の開発に伴い水需要が増しているが，河川流量の観測が行われていない地域では水資源利用計画の立案に大きな障害をもたらしている．この問題を解決するため，本論文は現在整備されつつある地球数値地図に着目して，標高，土地利用，地質等のデータを用いて流出モデルパラメータを推定し，分布型流出モデルの自動作成によって各地域の水資源評価を試みたものである．本論文は全７章よりなる．

第１章は序論であり，既往の研究から最新の研究のレビューを行い，本研究の位置を説明している．

第２章では，収集した数値地図情報と気象データによって，メコン河流域の地理や気候条件の説明を行っている．加えてメコン地域の一般問題や近年の開発状況について言及している．

第３章では分布型流出モデルの作成に必要となる擬似河道網作成法を新たに開発した．従来，デジタル標高データ（DEM）から流水方向を知る擬似河道網の作成アルゴリズムは，くぼ地や広い平地について流水方向を決めることが出来ない問題を抱えていた．そのため，グリッドサイズの変更により，流れの方向性を決めて，詳細な領域において決定するという新しいアルゴリズムを導入し，河道網を作成することに成功した．この方法によってほとんどの地域において擬似河道網を作成することが可能になった．また，DEM から任意流域の抽出も可能になり，各流域データセットの作成が容易になった．これらは重要な成果である．

第４章では，流出モデルのブロック TOP モデル（BTOP）と流路のマスキンガム・クンジモデル（MC）の構築について説明している．BTOP－MC モデルは普通，分布型では用いられないが，ここでは第３章の結果を利用して分布型モデルの構築を行った．このモデルには貯留と蒸発散の推定も行えるため，水文過程の評価も可能である．これは重要な成果である．

第５章は，BTOP－MC モデルをメコン河流域に適用している．適用の際に流出過程の人為的操作についてのモデル化を試みている．すなわち灌漑とダムによる貯留，放流の効果を物理モデルに組み込むことに成功した．モデル推定値と実測値の違いに着目して，農作業と定常的なダム操作を新たな推定モデルとして土地利用データに基づいて分布型流出モデルに付加し，誤差 10％以下の流量推定が可能になった．また，BTOP－MC モデルのパラメータを土地利用データと標高データから推定する手法も示し，任意地点でのモデル構築の可能性について示した．これは重要な知見である．

第６章では，５章の結果を踏まえて，水文解析と水資源解析を行った．観測データがない僻地の水資源を表現する指標として可能水資源量と水資源貢献量を提案し，水資源分布と水資源環境について論じている．また，BTOP－MC モデルから得られた水文過程を過去に提案したモデルと比較し，その妥当性を確認した．ここで述べられた水資源評価法は地球上の任意地点において行える方法であり，実用上極めて重要な結果である．

第７章は結論である．

以上要するに本論文は，分布型流量予測モデルを数値地図から精度よく構築することに成功し，任意地域の水資源評価が可能になった．本手法は水資源計画や環境計画に大いに貢献できるものである．

よって，本論文は博士（工学）の学位論文として合格と認める．